Concurrent Systems

Nebenläufige Systeme

XI. Guarded Sections

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January 31, 2017

Agenda

Outline

Subject Matter

- discussion on abstract concepts as to **structural measures** suited in paving the way for non-blocking synchronisation
  - guarded sections: synchronise process-originated events[1]
  - pre-/postlude sections: synchronise hardware-originated events

[1] Not to be confused with "guarded commands" [4].

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  - however their requests to enter and pass through may be delayed
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  - using concepts such as the **promise** [7] or promise pipelining [12]
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- similar to an explicit ("eventual values" [9, 10]) or implicit **future** [2], it is shown how to deal with "direct-result critical sections"
  - using concepts such as the **promise** [7] or promise pipelining [12]
  - functional programming meets distributed computing for synchronisation
- one learns that guarded sections largely resemble conventional critical sections, but with a much more relaxed execution model

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Mechanism of a (soft- or hardware) processor to prompt software to draw attention to an external process asynchronously, unpredictable, and unreproducible.

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- as to operating systems, usually a **trinity** of problem-specific routines is to be considered—and assumed in the following:

  guardian
  - *interrupt-handler dispatcher* running at CPU priority

  prelude
  - *first-level interrupt handler* (FLIH) running at CPU/OS priority

  postlude
  - *second-level interrupt handler* (SLIH) running at OS priority

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- what all have in common is the **asynchronism** to the current process that was interrupted and will be delayed by their particular actions

Responsibility Assignment (Ger.) *Aufgabenverteilung*

Hint (Interrupt Latency)

*In order to make **loss of interrupts** improbable, CPU priority[a] must be cancelled and OS priority[b] must be taken in minimum time.*

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- in case of an **edge-triggered** IRQ, takes OS priority <u>before</u> it
- identifies and activates the prelude for the given IRQ
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postlude
- operates the device, if still required, and particularly the system
- starts when no more preludes are stacked and, thus, pending
- as the case may be, interacts with a process instance

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Relevance of Postlude

Hint (Asynchronous System Trap, AST [11, p. 414])

On the VAX, a software-initiated interrupt to a service routine. ASTs enable a process to be notified of the occurrence of a specific event asynchronously with respect to its execution. In 4.3 BSD, ASTs are used to initiate process rescheduling.

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  - a mechanism that forces an interrupted process back into system mode:
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guardian	▪ not applicable, controls prelude and postlude (i.e., an AST)	☹
prelude	▪ risk of race conditions <u>and</u> system-stack overflow	☹
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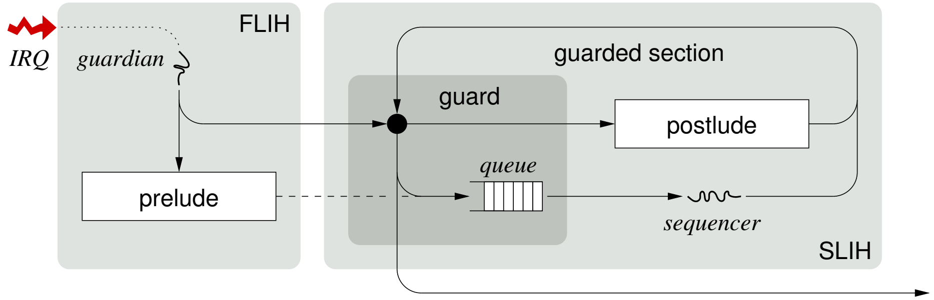
- purpose of the postlude is to safely allow such control-flow expansions
  - its activation is controlled similar to the control of guarded sections

Execution Sequencing of Postludes



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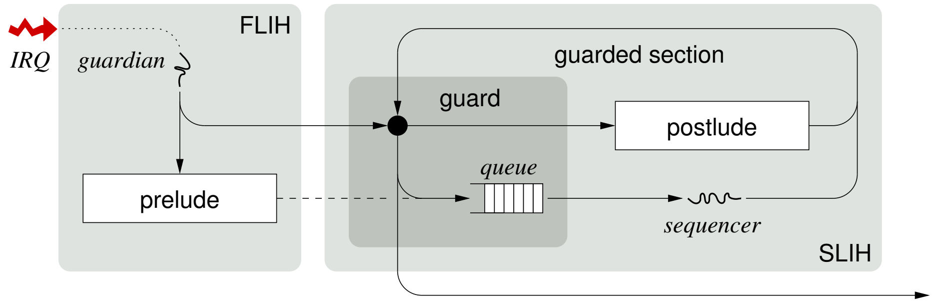

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  - a prelude is a **function**, its return value indicates the postlude to be run
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- according to the model, an interrupt indeed causes a new process but not a new process instance
  - the guardian is such a process, it operates in the name of the interrupted process instance and commands no own context
  - same applies for the sequencer, it is an optional **guardian continuation** and takes care for safe postlude processing

Overlapping Pattern

- not unlike the guarded section as to process events described below (cf. p. 20), but with the following fundamental differences:
  - simultaneous requests to run through a guarded section occur **stack-wise**
  - processing start as to delayed (i.e., pending) passage requests is **AST-like**
  - postludes are still carried out **asynchronously** to the interrupted process

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  - i higher priority preludes may overlap lower priority preludes
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- this **multiple-enqueue/single-dequeue** mode of operation eases the design of a non-blocking synchronised postlude queue

Guardian and Sequencer

From FLIH to SLIH (cf. p. 36*ff.*)

```
__attribute__ ((fastcall)) void guardian(long irq) {
    static usher_t tube = { 0, {0, &tube.load.head} };
    extern remit_t *(*flih[])(usher_t *);
    remit_t *task;

#ifdef __FAME_INTERRUPT_EDGE_TRIGGERED__
    pivot(&tube.busy, +1); admit(IRQ);  /* take OS priority */
#endif

    task = (*flih[irq])(&tube);         /* activate prelude & satisfy IRQ source */

#ifdef __FAME_INTERRUPT_LEVEL_TRIGGERED__
    pivot(&tube.busy, +1); admit(IRQ);  /* take OS priority */
#endif

    if (tube.busy > 1) {                /* sequencer is already on duty */
        if (task != 0) deter(&tube, task);  /* enqueue postlude & */
        avert(IRQ);                     /* leave with CPU priority */
    } else {                            /* bring sequencer into service */
        if ((task != 0) && (tube.load.head.link == 0)) remit(task);

        avert(IRQ);                     /* prevent lost unload */
        while (tube.load.head.link != 0) {
            admit(IRQ);                 /* take OS priority, again */
            flush(&tube);               /* forward pending postludes */
            avert(IRQ);                 /* leave with CPU priority */
        }
    }
    pivot(&tube.busy, -1);              /* leave critical section */
}
```


Lock-Free Synchronised Enqueue

cf. [14]

- assuming that simultaneous enqueues can happen only in a **stacking arrangement**, then the following is “thread safe”:

```
void chart_ms_lfs(queue_t *this, chain_t *item) {
    chain_t *last;

    item->link = 0;           /* terminate chain: FIFO */

    last = this->tail;        /* settle insertion point */
    this->tail = item;        /* create new partial list */

    while (last->link != 0)   /* overlapping enqueue! */
        last = last->link;    /* find end of orig. list */

    last->link = item;        /* insert & combine lists */
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- idea is to create a new partial list using an **atomic store** and, thus, isolate the original list for later safe manipulation
  - but simultaneous enqueues then may shift the **actual insertion point**

Lock-Free Synchronised Dequeue

cf. [14]

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chain_t *fetch_ms_lfs(queue_t *this) {
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    if ((item = this->head.link)  /* next item fetched */
    &&  !(this->head.link = item->link)) {
        this->tail = &this->head;  /* is last one, reset */
        if (item->link != 0) {      /* overlapping enq.! */
            chain_t *help, *lost = item->link;
            do {                    /* recover latecomers */
                help = lost->link;   /* remember next & */
                chart_ms_lfs(this, lost);  /* rearrange */
            } while ((lost = help) != 0);
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- critical is dequeuing as to the **last element** and overlapped by one or more enqueues, thus, filling up the queue again
  - one moment the fetched item was last, now latecomers must be recovered

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Hint (Lock Freedom)

Some process will complete an operation in a finite number of steps, regardless of the relative execution speeds of the processes. [8, p. 142]

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Wait-Free Solution

Special Instructions

```
void chart_ms_wfs(queue_t *this, chain_t *item) {
    chain_t *last;
    item->link = 0;      /* terminate chain: FIFO */
    last = FAS(&this->tail, item);
    last->link = item;  /* eventually append item */
}

chain_t *fetch_ms_wfs(queue_t *this) {
    chain_t *item = this->head.link;
    if (item) {            /* check for last item */
        if (item->link) /* is not, non-critical */
            this->head.link = item->link;
        else if (CAS(&this->tail, item, &this->head))
                CAS(&this->head.link, item, 0);
    }
    return item;
}
```

- with the following mapping to GCC atomic intrinsic functions:

```
#define FAS(ref,val)  __sync_lock_test_and_set(ref, val)
#define CAS           __sync_bool_compare_and_swap
```

Recapitulation

- in the **pre-/postlude model**, sequencer becomes that process in the context of which interrupt handling is carried out
  - more precisely, the process at the bottom of an interrupt-handler stack
  - put differently, the interrupted process that "activated" the guard (p. 9)

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Hint (Pro-/Epilogue [15, 14])

*At first glance, interrupt handler pre-/postludes seemingly resemble the pro-/epilogue model. While this is quite true for preludes, it does not hold for postludes. Epilogue execution is a **synchronous event** as to the interrupted kernel-level process, in contrast to postludes.*

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- postlude guide through is not unlike **procedure chaining** [13, p. 10], a technique to serialize execution of conflicting threads
  - differences are due to the constrained pre-/postlude overlapping pattern
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  - differences are due to the constrained pre-/postlude overlapping pattern
  - unless stack-based scheduling [1], any process overlapping is assumed
- this similarity gives reason to think about a **generalisation** of the pre-/postlude model to synchronise **process-*instance*** events

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Preface

Hardware Events
- Fundamentals
- Sequencing
- Implementation

Process Events
- Fundamentals
- Sequencing
- Implementation

Summary

Critical Sections Revisited

- assuming a **stack** represented as LIFO (*last in*, *first out*) single-linked list, whose *push*- and *pop*-operations need to be critical sections

```
void push(lifo_t *list, chain_t *item) {
    acquire(&list->lock);        /* enter critical section */
    item->link = list->link;
    list->link = item;
    release(&list->lock);        /* leave critical section */
}
```

```
chain_t *pull(lifo_t *list) {
    chain_t *item;

    acquire(&list->lock);        /* enter critical section */
    if ((item = list->link) != 0)
        list->link = item->link;
    release(&list->lock);        /* leave critical section */

    return item;
}
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    item->link = list->link;
    list->link = item;
    release(&list->lock);        /* leave critical section */
}
```

- processes proceed successively, <u>neither</u> depends on the computation result

```
chain_t *pull(lifo_t *list) {
    chain_t *item;

    acquire(&list->lock);        /* enter critical section */
    if ((item = list->link) != 0)
        list->link = item->link;
    release(&list->lock);        /* leave critical section */

    return item;
}
```

- processes proceed successively, <u>each</u> depends on the computation result

Conditional Fire-and-Forget Pattern

- in the final analysis, critical sections are **twofold**, namely one that is *procedure*- and another one that is *function*-like
  - with the former delivering no direct result, in contrast to the latter

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  - thus, critical-section execution is **asynchronous** to its requesting process
- in case of data dependencies as to the computation within a critical section, synchronisation on **result delivery** becomes necessary
  - thereto, computation results need to be returned and accepted **by proxy**
  - to this end, the following measures have to be provided:
    - i as additional element of the corresponding passage request, a placeholder for the computation result (*consumable resource*) and
    - ii a signalling mechanism to indicate result delivery (*logical synchronisation*)

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... guarded sections

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Handling of a Cirtical-Section Function

Direct Result

- fall back on known **linguistic concepts** in order to pattern a solution for the above-mentioned problem:

  future
  - the *promise* to deliver a value at some later point in time [2]
  - read-only placeholder object created for a not yet existing result
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  kept
  - value computed, assignment took place

  broken
  - computation aborted, assignment ceases to take place

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    - computation aborted, assignment ceases to take place
  - pending
    - process in progress, assignment did not just yet take place
- based on these states, a process is able to synchronise on the **event** that the promise to deliver a value was either kept or broken
  - the resolver (process inside the critical section) acts as producer
  - the future using process acts as consumer $\rightsquigarrow$ ***signalling semaphore***

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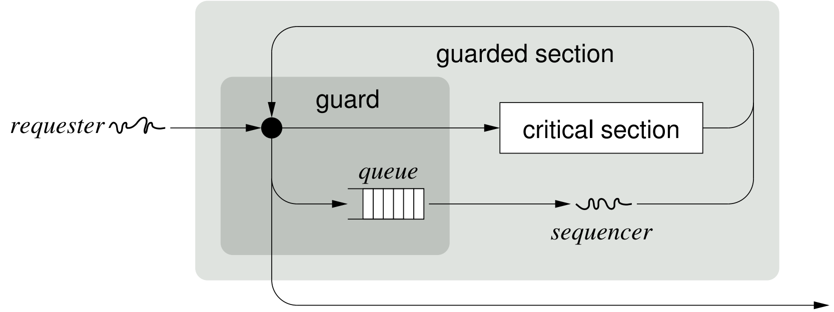
Execution Sequencing of Critical Sections



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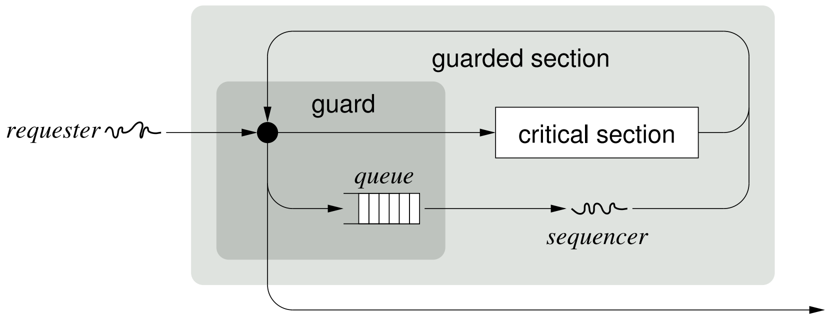

- heading for a critical section depending on the **state of occupancy**:
  - unoccupied
    - guard grants requester access to the critical section
    - the critical section becomes occupied by the requester
  - occupied
    - guard denies requester access to the critical section
    - the request gets queued and the requester bypasses

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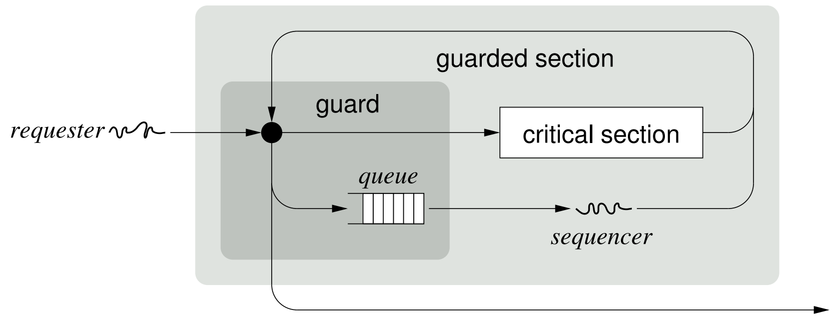

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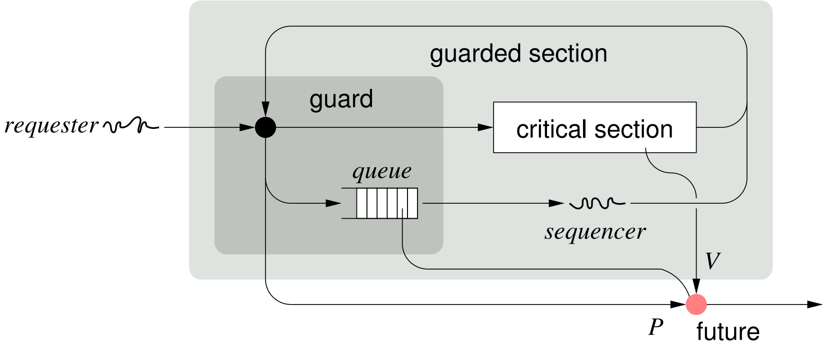
    - the request gets queued and the requester bypasses
- leaving a critical section depending on the **request-queue state**:
  - empty
    - critical section becomes unoccupied, the process continues
  - full
    - the actual leaving process becomes sequencer and re-enters the critical section for each queued request

Synchronisation of Direct-Result Critical Sections



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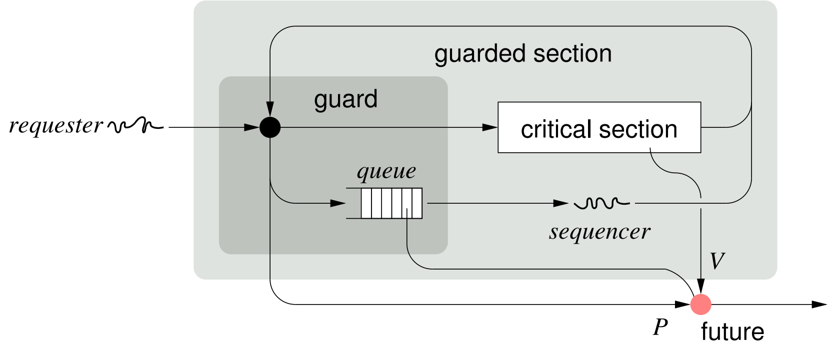

- a passage request may refer to a multi-elementary **future object**:
  - i a promise indicator (kept, broken, pending)
  - ii a placeholder of problem-specific type as to the critical section
  - iii a binary semaphore that is used in producer/consumer mode
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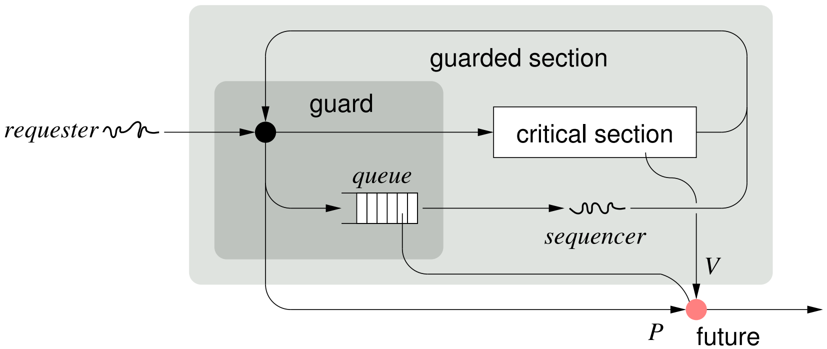

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    - i.e., a **signalling semaphore** applicable by different processes
- in case of a direct-result critical section, the sequencer takes the part of a **resolver** that also have to signal the "kept" or "broken" state
  - V does the signalling and by means of P the signal can be consumed

Execution Characteristics of the Critical Section

- critical sections controlled by processes in a **run-to-completion style** can be handled straightforwardly

Definition (Run to Completion (Process))

A potentially preemptive process free from self-induced wait states as to the possible non-availability of reusable or consumable resources.

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- both styles of execution concern the period of a critical section, only
  - but at large, a process may be classified run to completion <u>and</u> stopover

Run-to-Stopover for Peer Processes

- critical sections controlled by processes waiting on events caused by **external processes** can be handled straightforwardly
  - as the external process, in order to making progress, does not depend on any internal process or state of any critical section
  - thus, interaction between external and internal processes is **non-critical**[3]

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    - if the consumer needs to wait on the producer inside a critical section
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  - other "critical interaction" is implicit subject matter of any critical section
- as a consequence, **precautions** must be taken for interacting internal processes—similar to signalling inside monitors [16, p. 9]
  - without clearing the guarded section, a **stopover process** may deadlock

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- regarding the whole request processing chain and the involvement of requester and sequencer process one may realise:
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Hint (Wait Freedom)

Any process can complete any operation in a finite number of steps, regardless of the execution speeds of the other processes. [8, p. 124]

Data Type I

Critial-Section Guard

```
typedef struct guard {
    int book;             /* # of concurrent requests */
    queue_t load;         /* pending passage requests */
#ifdef __FAME_GUARD_ADVANCED__
    ...
#endif
} guard_t;
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- invariably, a **chain-like queue** of registered “passage requests”
  - mandatory, sufficient for elementary guarded sections
  - with a twofold meaning of the *book* attribute depending on its value
    - i the actual number of passage requests pending for processing
    - ii the state of occupancy (cf. p. 20): occupied if *book* > 0, unoccupied else

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  - with a twofold meaning of the *book* attribute depending on its value
    - i the actual number of passage requests pending for processing
    - ii the state of occupancy (cf. p. 20): occupied if *book* > 0, unoccupied else
- variably, additional stuff for advanced control of guarded sections:
  - some **timeout** that ensures progress for the actual **major sequencer**
  - a **minor sequencer** to replace the major sequencer at timeout
  - any management data to prevent **priority inversion**, if applicable
  - ...

Claiming

first-come, any serve (FCAS)

- vouch for sequential execution of a guarded critical section:

```
1 inline order_t *vouch(guard_t *this, order_t *work) {
2     enqueue(&this->load, work);
3     if (FAA(&this->book, 1) == 0)
4         return dequeue(&this->load);
5     return 0;
6 }
```

2 - remember this passage request
3 - check state of occupancy and book passage request
4 - was unoccupied, became sequencer, accept first passage request
  - could be a request different from the one that was just remembered

Claiming and Clearing

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3 - check state of occupancy and book passage request
4 - was unoccupied, became sequencer, accept first passage request
  - could be a request different from the one that was just remembered

- clear the next passage request, if any, pending for processing:

```
7 inline order_t *clear(guard_t *this) {
8     if (FAA(&this->book, -1) > 1)
9         return dequeue(&this->load);
10    return 0;
11 }
```

8 - count completion and check for further pending requests
9 - remove next passage request, if any available

Data Type II

Passage Request

```
typedef struct order {
    chain_t next;        /* passage-request chaining */
    item_t post;         /* argument placeholder */
} order_t;
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- layout of an **argument vector** for passage-request parameters:

```
typedef union item {
    long (*lump)[];     /* argument vector (N > 1) */
    long sole;          /* single argument (N = 1) */
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  - depending on the number of parameters, the structure describes a multi- or uni-element argument vector
  - in the multi-element case, the argument vector is placed adjacent to its item or order, resp., instance (cf. p. 41)

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  - in the multi-element case, the argument vector is placed adjacent to its item or order, resp., instance (cf. p. 41)
- in addition, this vector also serves as placeholder for a *future value*

Piece the Puzzle Together

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- fore **editing** of passage-request parameters, optional:

```
order_t *task = order(2);           /* two parameters */
(*task->post.lump)[0] = (long)index;
(*task->post.lump)[1] = value;
```

Piece the Puzzle Together

- **entry protocol**, agreement on the sequencer process:

```
extern guard_t gate;
if (vouch(&gate, task)) do                  /* enter section */
```


Piece the Puzzle Together

- midsection (i.e., actual critical section), **solo attempt**:

```
/* Several Species of Small Furry Animals
 * Gathered Together in a Cave and
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- **exit protocol**, processing of pending passage requests:

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while ((task = clear(&gate)));          /* leave section */
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- **exit protocol**, processing of pending passage requests:

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  - besides logical synchronisation in the **midsection**, any other programming statements are doable as well—like in conventional critical sections

Outline

Résumé

- guarding of critical sections at operating-system as well as instruction set architecture level and in a non-blocking manner
  - processes are never delayed at entrance of an already occupied critical section, however their requests to pass through
  - not unlike **procedure chaining**, but also supporting in-line functions
- at both levels, overlappings as to simultaneous processes result in a **multiple-enqueue/single-dequeue** model of request handling
  - the **sequencer** will be the only process being in charge of dequeuing
  - that is, the continuation of a **requester** (lev. 3) or the **guardian** (lev. 2)[4]
  - whereby this continuation is **commander-in-chief** of a critical section
- when a requester process requires a direct result from the sequencer process, interaction in a consumer/producer-style takes place
  - in such a case, the respective request is associated with a **future object**
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  - a future-specific **signalling semaphore** then indicates result availability
- besides supporting conventional critical sections, this approach eases design of non-blocking synchronised non-sequential programs

[4] Operating-sytem machine or instruction set architecture level, respectively.

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- besides supporting conventional critical sections, this approach eases design of non-blocking synchronised non-sequential programs

[4] Operating-sytem machine or instruction set architecture level, respectively.

Résumé

- guarding of critical sections at operating-system as well as instruction set architecture level and in a non-blocking manner
  - processes are never delayed at entrance of an already occupied critical section, however their requests to pass through
  - not unlike **procedure chaining**, but also supporting in-line functions
- at both levels, overlappings as to simultaneous processes result in a **multiple-enqueue/single-dequeue** model of request handling
  - the **sequencer** will be the only process being in charge of dequeuing
  - that is, the continuation of a **requester** (lev. 3) or the **guardian** (lev. 2)[4]
  - whereby this continuation is **commander-in-chief** of a critical section
- when a requester process requires a direct result from the sequencer process, interaction in a consumer/producer-style takes place
  - in such a case, the respective request is associated with a **future object**
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Guardian Insulating and Invoking

```
_joint:
    pushl %ecx      # save volatile register
    movl  $0, %ecx  # pass IRQ number
_jointN:            # come here for IRQ number N > 0
    pushl %edx      # save another volatile register
    pushl %eax      # ditto
    call  _guardian # fastcall to guardian
    popl  %eax      # restore volatile register
    popl  %edx      # ditto
    popl  %ecx      # ditto
    iret            # resume interrupted process
```

- each IRQ entry in the CPU exception vector is associated with a *joint*

```
_joint42:
    pushl %ecx      # save volatile register
    movl  $42, %ecx # pass IRQ number
    jmp   _jointN   # switch to common joint section...
```

S{a,i}mple Interrupt Handler

- first-level interrupt handler (FLIH), at CPU/OS priority (p. 11, l. 7)

```
1 remit_t *prelude(/*optional*/usher_t *tube) {
2     static remit_t task = { {}, postlude};
3     /* Come here for device pre-processing &
4      * device-related IRQ acknowledgement. */
5     deter(tube, &task); /* force postlude to queue */
6     return 0;           /* don't request shortcut */
7 }
```

  - without l. 5, **postlude shortcut** (p. 11, l. 20) goes with `return &task`

- second-level interrupt handler (SLIH), at OS priority (p. 11, l. 7/13)

```
void postlude(/*optional*/order_t *todo) {
    /* Come here for device post-processing &
     * any asynchronous system interaction. */
    V((semaphore_t *)todo->post.sole);
}
```

  - system interaction means: to *vouch* for guarded sections (cf. p. 28)

Interrupt-Handler Guard

- a **doorman** (Ger. *Pförtner*) for guarded sections at the low level of handling asynchronous program interrupts, a **specialised guard**:

```
typedef guard_t usher_t;

inline void deter(usher_t *tube, remit_t *task) {
    chart(&tube->load, &task->data.next);
}

inline remit_t *untie(usher_t *tube) {
    return (remit_t *)fetch(&tube->load);
}

inline void flush(usher_t * tube) {
    remit_t *next;
    do if ((next = untie(tube))) remit(next);
    while (next != 0);
}
```

  - with queue synchronisation style: `#define __FAME_SYNC_ITS__`
    - resulting in "`{chart,fetch}_ms_lfs`" or -"`_wfs`", resp.

Job Definition and Start

- a SLIH or an interrupt-handler postlude, resp., is a **passage request** (cf. p. 27) attended by a procedure address
  - that is to say, a request object with implicit processing method

```
typedef struct remit {
    order_t data;                /* parameter set */
    void (*code)(order_t *);     /* procedure address */
} remit_t;

inline void remit(remit_t *this) {
    (*this->code)(&this->data); /* run that job */
}
```

- at process-event level, this structure specifies different **parameterised critical sections** associated with the same guarded section
  - it allows for **procedure chaining** similar to that of Synthesis [13, p. 10]

Art of Waiting

- straightforward is the use of a **signalling semaphore**[5]:

```
typedef semaphore_t indicator_t;
inline void enroll(indicator_t *hint) { }
inline void repose(indicator_t *hint) { P(hint); }
inline void arouse(indicator_t *hint) { V(hint); }
```

  - note that a semaphore has **memory semantics** with regard to signals
  - thus, awaiting a signal by means of *P* once a sequencer process released the guarded section is free of the lost-wakeup problem
  - a *V* saves the signalling event in the semaphore, causing *P* to continue

- another option is falling back on the **event queue** [16, p. 17]:
  - just if one wants to implement *P* and *V* as a guarded section, for example

```
typedef event_t indicator_t;
inline void enroll(indicator_t *hint) { catch(hint); }
inline void repose(indicator_t *hint) { coast(); }
inline void arouse(indicator_t *hint) { cause(hint); }
```

[5] A **binary semaphore** used in a producer/consumer style of interaction.

Order Allocation/Deallocation

```
inline order_t *order(unsigned long n) {
    order_t *item;
    if (n < 2)
        item = (order_t *)malloc(sizeof(order_t));
    else {
        item = (order_t *)
            malloc(sizeof(order_t) + n * sizeof(long));
        if (item)
            item->post.lump = (void *)
                ((long)item + sizeof(*item));
    }
    return item;
}

inline void ditch(order_t *item) {
    free(item);
}
```

- in oder to decrease latency and lower overhead, specialisation towards the use of an **order pool** is recommended

Data Type III


```
typedef struct future {
    promise_t data;      /* prospective value */
    indicator_t gate;    /* signalling element */
} future_t;
```

- a future object is the promise—of a guarded section, here—to deliver a result at some later point in time:

```
typedef enum status {
    PENDING, KEPT, BROKEN
} status_t;

typedef struct promise {
    status_t bond;       /* processing state */
    item_t item;         /* future-value placeholder */
} promise_t;
```

  - whereby the promise is a result placeholder, on the one hand, and keeps track of the status of result delivery, on the other hand

S{a,i}mple Future Implementation

```
inline status_t probe(future_t *this) {
    return this->data.bond;
}

inline void trust(future_t *this) { enroll(&this->gate); }

inline item_t *exact(future_t *this) {
    repose(&this->gate);
    return probe(this) == KEPT ? &this->data.item : 0;
}

inline void bring(future_t *this, status_t bond) {
    this->data.bond = bond;
    arouse(&this->gate);
}

inline void prove(future_t *this, item_t *item) {
    this->data.item = *item;
    bring(this, KEPT);
}

inline void abort(future_t *this) { bring(this, BROKEN); }
```